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Multi-Model Validation of Currents in the Chesapeake Bay Region in June 2010

PHILIP Y. CHU, GREGG A. JACOBS,[1] M. KEMAL CAMBAZOGLU,[2] AND ROBERT S. LINZELL[3]

[1]Naval Research Laboratory, Stennis Space Center, Mississippi, USA
[2]University of Southern Mississippi, Stennis Space Center, Mississippi, USA
[3]QinetiQ North America Inc., Stennis Space Center, Mississippi, USA

In this paper, we discuss the validation of water level and current predictions from three coastal hydrodynamic models and document the resource and operational requirements for each modeling system. The ADvanced CIRCulation Model (ADCIRC), the Navy Coastal Ocean Model (NCOM), and Delft3D have been configured and validated for the Chesapeake Bay region during a Navy exercise. Water level predictions are compared with a NOAA/NOS water level gauge at the Chesapeake Bay Bridge Tunnel location while current predictions are validated with Acoustic Doppler Profiler (ADP) measurement records at three locations in the lower Chesapeake Bay. Statistical metrics such as correlation coefficient and root mean square error (RMSE) are computed. Both the vertically-integrated currents and currents at varying water depths are compared as well. The model-data comparisons for surface elevation indicate all three models agreed well with water level gauge data. The two-dimensional version of ADCIRC, ADCIRC2D, and NCOM yield better statistics, in terms of correlation and RMSE, than Delft3D. For vertically-integrated currents, ADCIRC2D has the smallest RMSE at Thimble Shoal and Naval Station locations while NCOM has the smallest RMSE at Cape Henry. For the horizontal currents over the water column, the fully three-dimensional, baroclinic ADCIRC model, ADCIRC3D, and NCOM both showed better agreement with the ADP measurements.

Keywords Chesapeake Bay, model validation, coastal models, currents, water levels, NCOM, Delft3D, ADCIRC

1. Introduction

There is a strong need for the U.S. Navy to develop relocatable, operational coastal forecast systems to support naval missions in coastal and semi-enclosed seas. Naval Research Laboratory (NRL) has been actively working on the development of multiple global and regional ocean models for that purpose (Chu et al. 2009). Navy Coastal Ocean Model (NCOM), ADvanced CIRCulation Model (ADCIRC), and DELFT3D are some of those models. Products of those models such as water levels, currents and temperature are used to support fleet navigation, Mine Warfare (MIW), diver operations, and so forth.

Received 28 October 2011; accepted 6 June 2012.
Address correspondence to Philip Chu, Naval Research Laboratory, Stennis Space Center, MS 39529, USA. E-mail: chu@nrlssc.navy.mil

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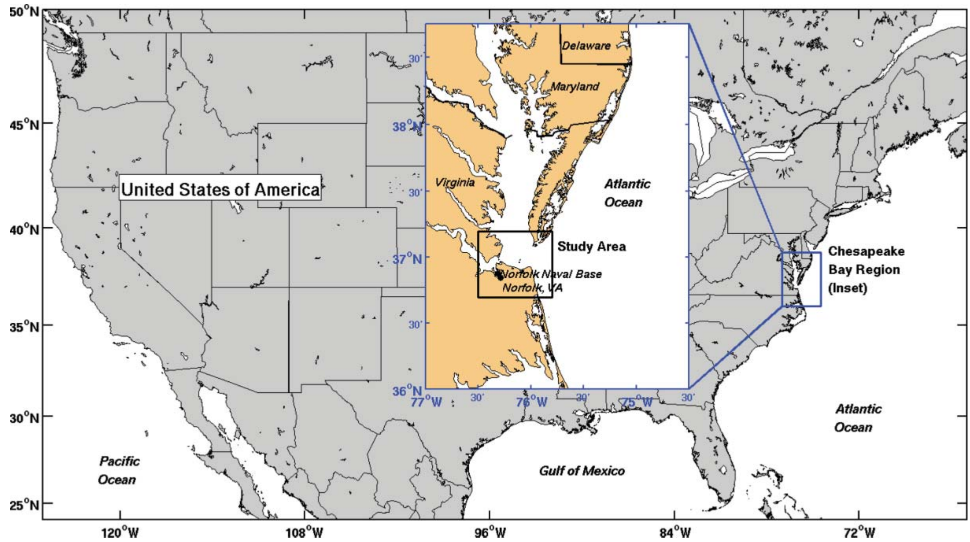

Figure 1. The U.S. map and Chesapeake Bay location. (Color figure available online.)

A Navy exercise in the lower Chesapeake Bay region during June 2010 provided an excellent opportunity to validate the accuracy and performance of these models. Chesapeake Bay lies on the eastern coast of the United States (Figure 1). It is the largest inlet along the U.S. Atlantic Coastal Plain and is the largest estuary in the United States. It lies off of the Atlantic Ocean and is surrounded by the states of Virginia and Maryland. The study area focuses on the region surrounding the U.S. Naval Station, Norfolk, Va., slightly more than 33 km west of mouth of the bay. The primary bathymetric feature of this area is Thimble Shoal Channel. The NOAA station at Thimble Shoal and the seaward extension of the channel are apparent in the bathymetric contours seen in Figure 13.

In this paper, we describe (1) the modeling effort by NRL scientists to support the exercise; (2) the validation and performance of water level and current predictions by three coastal hydrodynamic models: the ADCIRC, both in two-dimensional (ADCIRC2D) and three-dimensional, baroclinic (ADCIRC3D) forms, the NCOM and Delft3D; and (3) the resource requirements including hardware, personnel, training and operations for each modeling system. This paper is organized as follows: Section 2 describes model configuration and products. Observational and field data are summarized in Section 3. Model validation and skill assessment are detailed in Section 4. Resource issues and requirements for the modeling systems are discussed in Section 5. Conclusions are summarized in Section 6.

2. Model Configuration and Products

ADCIRC is a finite element-based community coastal circulation model that solves water surface elevation using the continuity equation in the Generalized Wave-Continuity Equation (GWCE) form and solves velocity using the momentum equations. Its unstructured grid and unique wetting/drying feature allows accurate modeling of complex coastlines and estuaries at fine spatial scales. This model can be run either in its two-dimensional (2D) depth-integrated mode or in a full three-dimensional, baroclinic mode. The detailed formulation and implementation of ADCIRC can be found in Luettich and Westerink (2004, 2005) and a recently published report by Blain et al. (2010). The two versions, ADCIRC2D

and ADCIRC3D, implemented for this validation exercise and their key differences are summarized below:

1) ADCIRC2D, the 2D depth-integrated code, is based herein on version 45.11 while ADCIRC3D, the fully three-dimensional baroclinic code as applied within is based on version 49.00.
2) ADCIRC2D computes a two-dimensional vertically-integrated velocity while ADCIRC3D computes a three-dimensional velocity field with 41 layers in the vertical direction using a generalized sigma coordinate system.
3) The mesh over which ADCIRC2D is applied has spatial resolution ranging from 15 m to 2 km; application of the ADCIRC3D model uses a coarser resolution mesh whose minimum element spacing is approximately 150 m.
4) Both ADCIRC2D and ADCIRC3D applies a tidal database as the open ocean boundary condition, but ADCIRC3D may also derive boundary and initial conditions from the U.S. East Coast NCOM forecasts.
5) ADCIRC3D has additional forcing in the form of surface wind and heat flux obtained from the Navy Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) (Hodur 1997) at its operational resolution of 27 km.

2.1. ADCIRC2D

The ADCIRC2D Chesapeake Bay model system was configured to cover the Chesapeake Bay, Delaware Bay and extends east to the Atlantic Ocean (73W-77W, 36N-40N). The mesh contained 318,860 nodes and 558,718 elements with 15 m spatial resolution in the lower Chesapeake Bay and shipping channels and approximately 2 km at the outer boundary. The grid bathymetry was derived from a combination of NOAA/NOS soundings, NOAA Electronic Navigation Charts (ENCs), and NOAA Raster Nautical Charts (RNCs). The tidal potential and tidal constituents applied at the open ocean boundary were extracted from a tidal database derived from the Western North Atlantic Ocean Tidal Model (Yang and Myers 2007); eight main tidal constituents were included: Q1, O1, K1, N2, M2, K2, S2, and P1. River discharge was determined to be negligible during the validation period and was therefore neglected. The bathymetry and numerical meshes for the computation domain are depicted, respectively, in Figures 2 and 3. The validation region in the lower Chesapeake Bay is shown in Figure 4.

The ADCIRC2D model system was configured in March 2010. After a brief spin-up and hindcast validation using historical records, daily predictions of water level and currents were produced starting in April 2010 and continued to run in real-time for the duration of the exercise period (June 4–11, 2010). In this study, ADCIRC is run in a parallel fashion on a cluster of computers. The parallel environment allows the use of multiple interconnected processors simultaneously to decrease runtimes. The model forecasts used a time step of 1 second and ran over 64 CPUs; at NRL, the daily forecast was executed on a Linux cluster using the Sun Grid Engine (SGE) queue system, on which a 72-hr forecast took approximately 1 hr. Identical runs were performed on the DoD Supercomputing Resources Center (DSRC) host "DaVinci" at the Naval Oceanographic Office (NAVOCEANO). The same model configuration also took approximately 1 hr of wall clock time for a 72-hr forecast. The daily products for the system included hourly two-dimensional maps of water levels and currents in the lower Chesapeake Bay (e.g., Figures 5 and 6). In addition, 6-min water level and current magnitude time series at ten locations were generated daily to support the exercise. Examples of these products are shown in Figures 7 and 8.

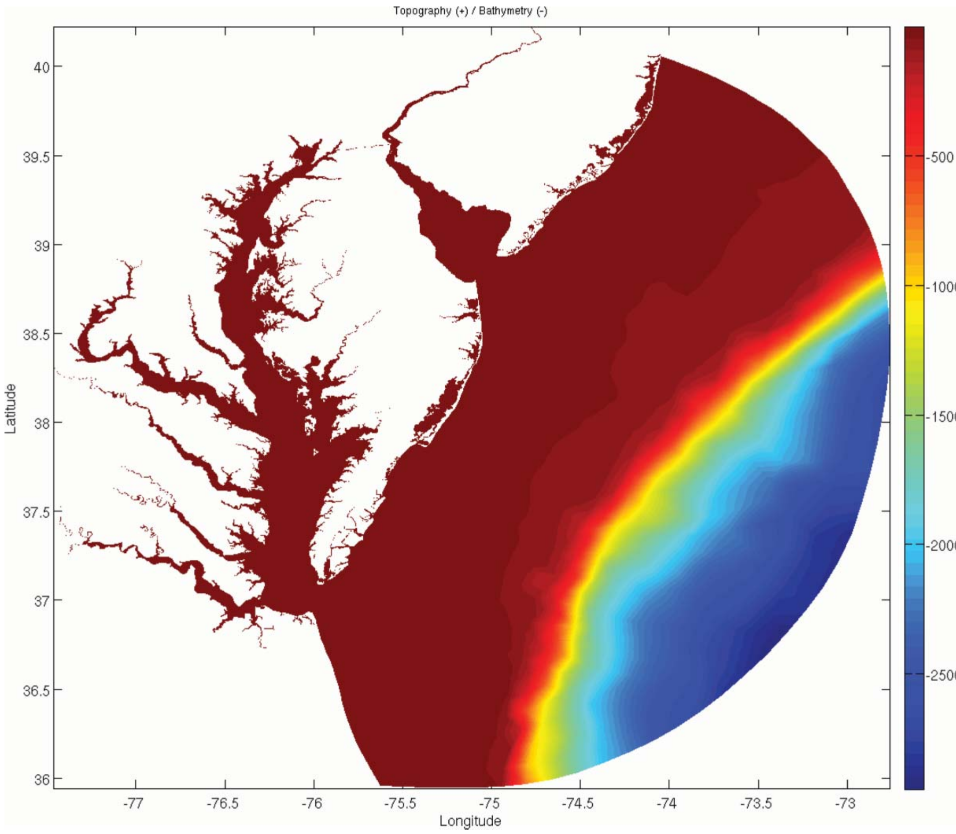

Figure 2. The bathymetry for the ADCIRC2D domain. (Color figure available online.)

2.2. ADCIRC3D

As described earlier, ADCIRC3D is the full three-dimensional (3D) baroclinic version of ADCIRC. This version of ADCIRC solves the transport equations for temperature and salinity using a terrain following generalized sigma vertical coordinate system in which the nodes can be distributed over the vertical direction. The stretched coordinate system is applied to all terms except the baroclinic pressure gradient to reduce known limitations when using sigma coordinates.

The ADCIRC3D domain has the same geographic coverage as the ADCIRC2D model but uses an unstructured mesh with 99,309 nodes, 192,051 elements leading to coarser resolution of about 150 m in the lower Chesapeake Bay; 41 uniformly distributed sigma layers are used over the vertical. The bathymetry of this mesh was interpolated from same sources as the ADCIRC2D model. Boundary and initial conditions were derived from the U.S. East Coast NCOM forecasts. COAMPS 27-km winds at 3-hr intervals were applied as surface meteorological forcing. The surface heat fluxes are calculated using latent, sensible heat fluxes, and shortwave and longwave radiation components provided by COAMPS. Similar to ADCIRC2D, river discharge was not included as boundary forcing.

ADCIRC3D runs start with a diagnostic phase during which the temperature, salinity, and density fields are unchanged. This is intended to spin-up the winds, tides, and other

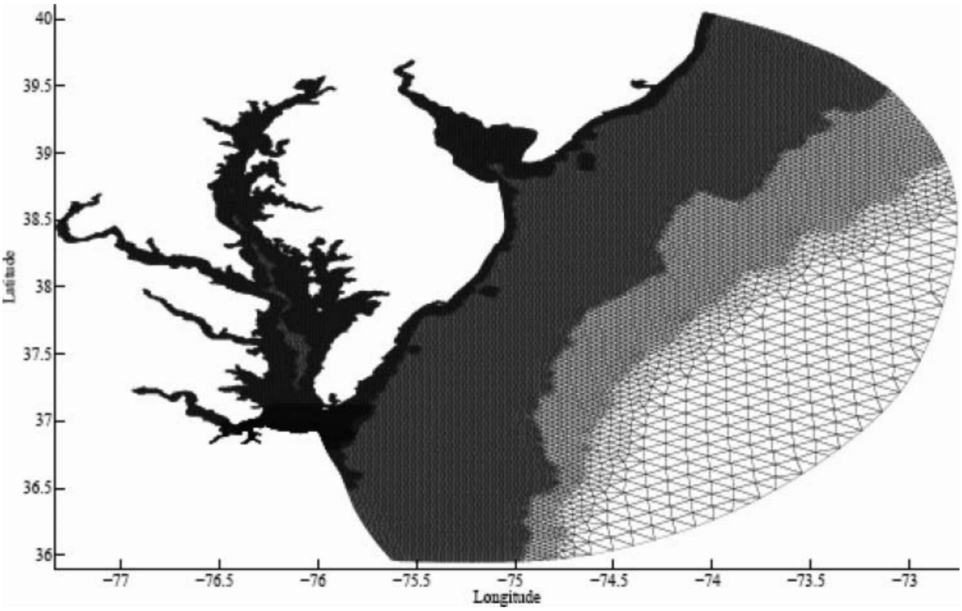

Figure 3. The unstructured mesh used for ADCIRC2D simulations.

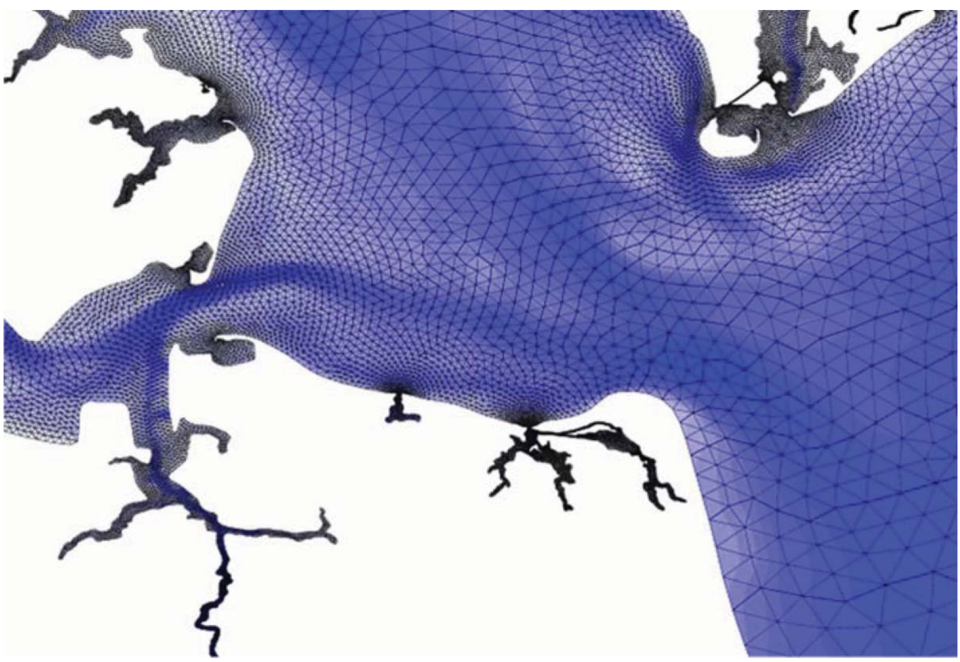

Figure 4. The unstructured mesh of the ADCIRC2D model in the lower Chesapeake Bay. (Color figure available online.)

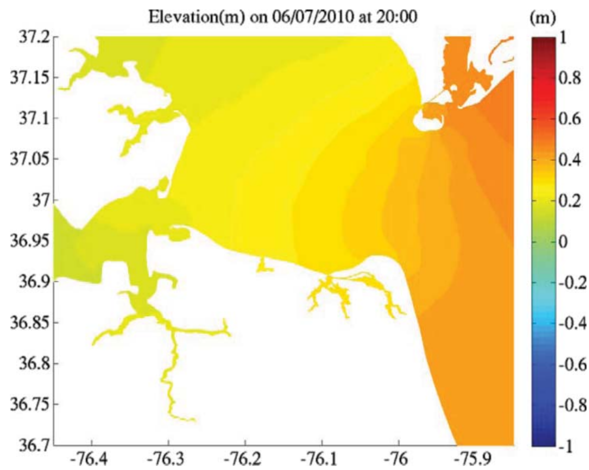

Figure 5. The water surface elevation result from ADCIRC2D on June 7, 2010. (Color figure available online.)

barotropic forcing. The diagnostic run is followed by a prognostic run in which full 3D baroclinic calculations are performed and the transport equations for temperature and salinity are solved producing density-driven currents. The Mellor-Yamada 2.5 turbulent closure scheme is selected as the vertical mixing scheme.

The ADCIRC3D system was configured for the Chesapeake Bay region using a time step of 5 s and again executing on 64 CPUs. The same SGE parallel computing cluster at NRL as was used for the ADCIRC2D application was used to make 72-hr diagnostic runs followed by 72-hr prognostic run simulations. Because of the computational requirements and the need to wait for the completion of NCOM forecasts that are applied as boundary

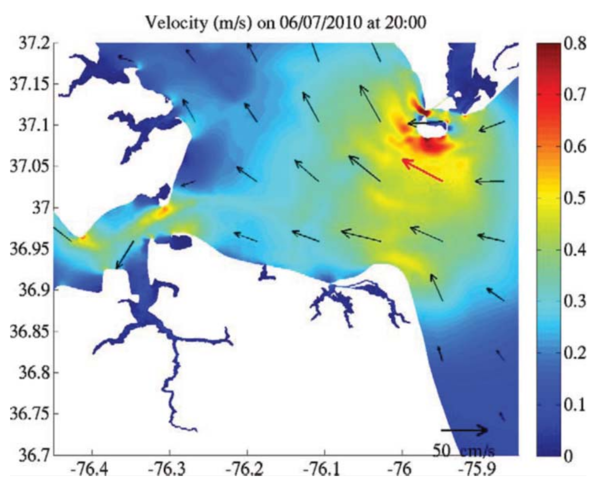

Figure 6. The depth-integrated current result from ADCIRC2D on June 7, 2010. Color is current magnitude and direction is shown by black arrows. (Color figure available online.)

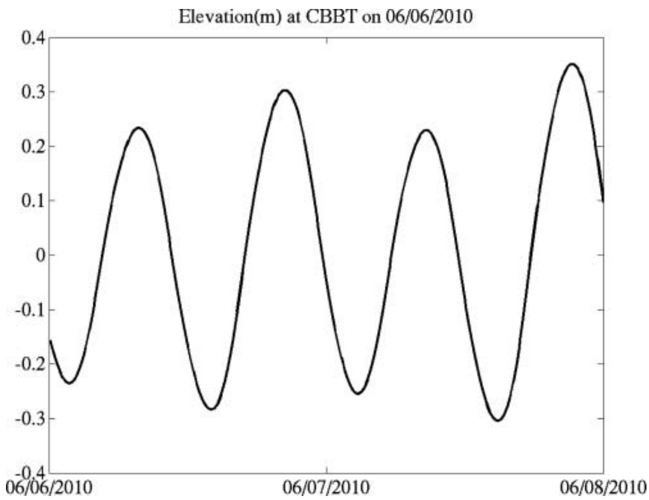

Figure 7. The water surface elevation results from ADCIRC2D from June 6–8, 2010, at the Chesapeake Bay Bridge Tunnel.

conditions, the ADCIRC3D runs were performed in a non-real time delayed mode. The simulations were run daily on 64 CPUs and required approximately 4 hrs of wall-clock time. The performance of the NRL SGE has been comparable to the performance Navy DSRC host DaVinci. Products of water level and horizontal current maps as well as station time series, identical to those produced by the ADCIRC2D system, are also produced by this system. Additional products include temperature, salinity, and horizontal current fields over the water column at 6-hr intervals.

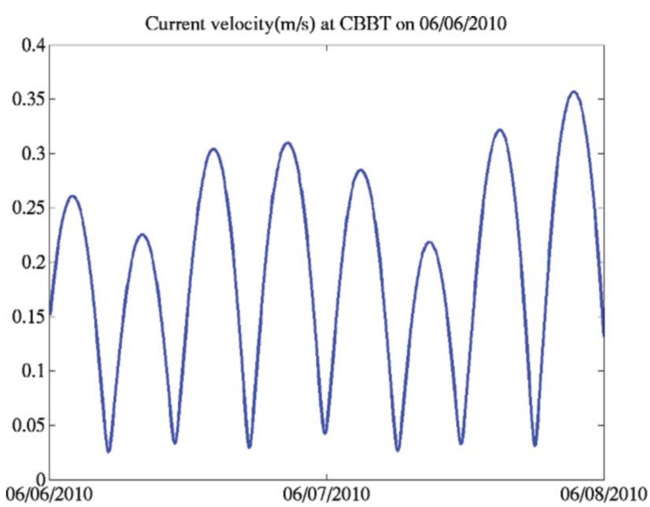

Figure 8. The depth-integrated current result from ADCIRC2D from June 6–8, 2010, at Chesapeake Bay Bridge Tunnel. (Color figure available online.)

2.3. NCOM

The Navy Coastal Ocean Model (NCOM) is a baroclinic, hydrostatic with Boussinesq approximation, free surface, data assimilated model developed by NRL. NCOM uses a Cartesian horizontal grid system, a flexible hybrid sigma-z in the vertical coordinate, an

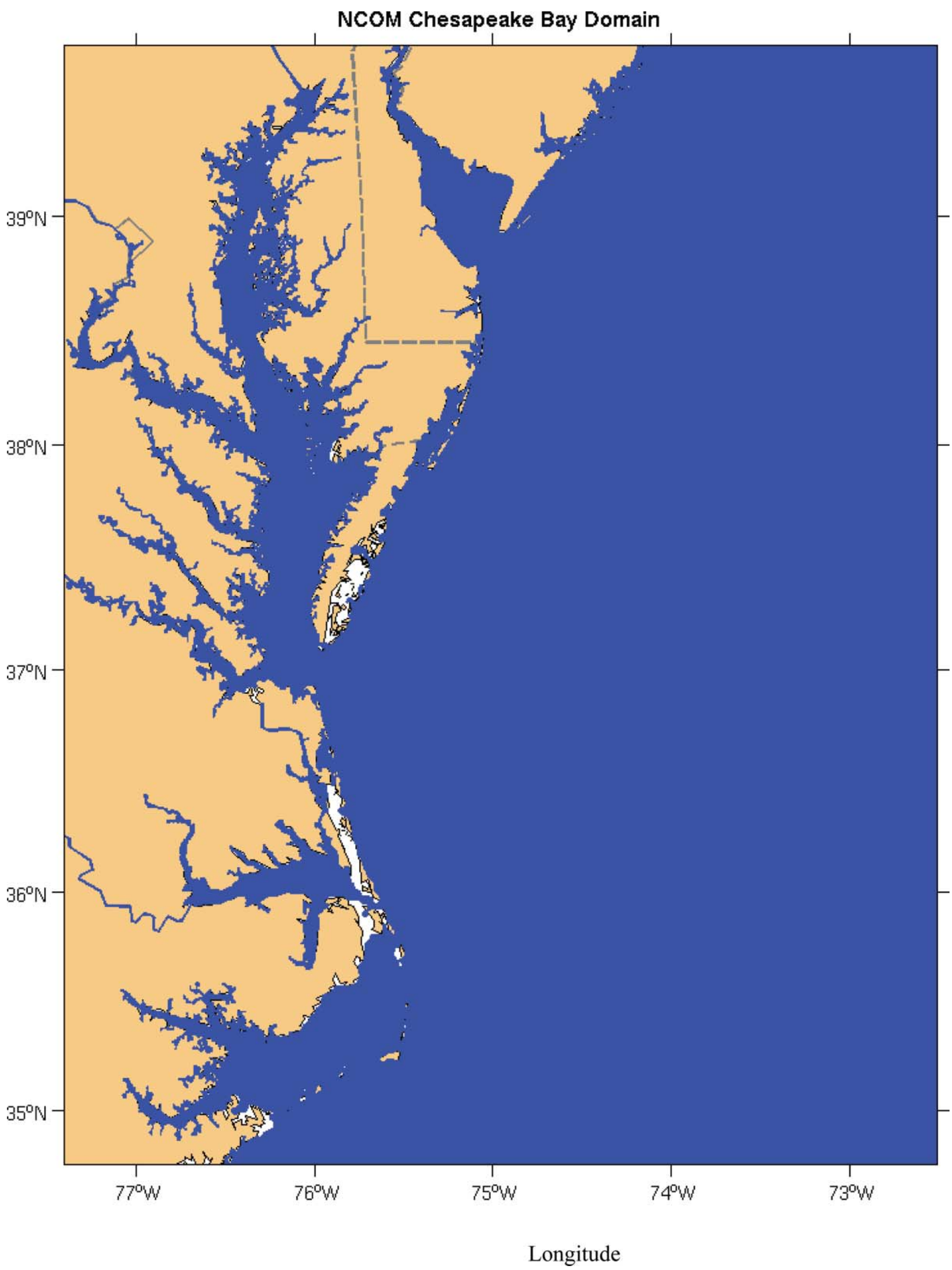

Figure 9. The Chesapeake Bay NCOM domain. (Color figure available online.)

implicit scheme for free surface, and Mellor-Yamada level 2 closure for the vertical mixing. Complete descriptions of the model formulation and implementation can be found in Martin (2000) and Barron et al. (2006). NCOM has been transitioned to the NAVOCEANO Operational Production Center to provide daily ocean forecasts to the U.S. Navy at global, regional and coastal scales (Rowley 2008, 2010).

The NCOM model in the Chesapeake Bay region for this exercise is configured in the following fashion: The domain is a 5-by-5 degree area (72.5W–77.5W, 34.5N–39.5N) that covers the Chesapeake Bay and part of the U.S. East Coast (Figure 9) at 500 m spatial resolution with 29 vertical layers. The computational domain included more than one million grid points. Bathymetry was derived from the NRL DBDB2 global bathymetry database. Boundary forcing and initial conditions were extracted from the East Coast NCOM which has a 3 km grid resolution. Surface meteorological forcing was applied using the COAMPS forecast meteorological fields.

The NCOM simulations were run daily on 128 CPUs at the Navy DSRC host DaVinci and required approximately 5 hrs of wall-clock time for 72-hr forecasts, including data

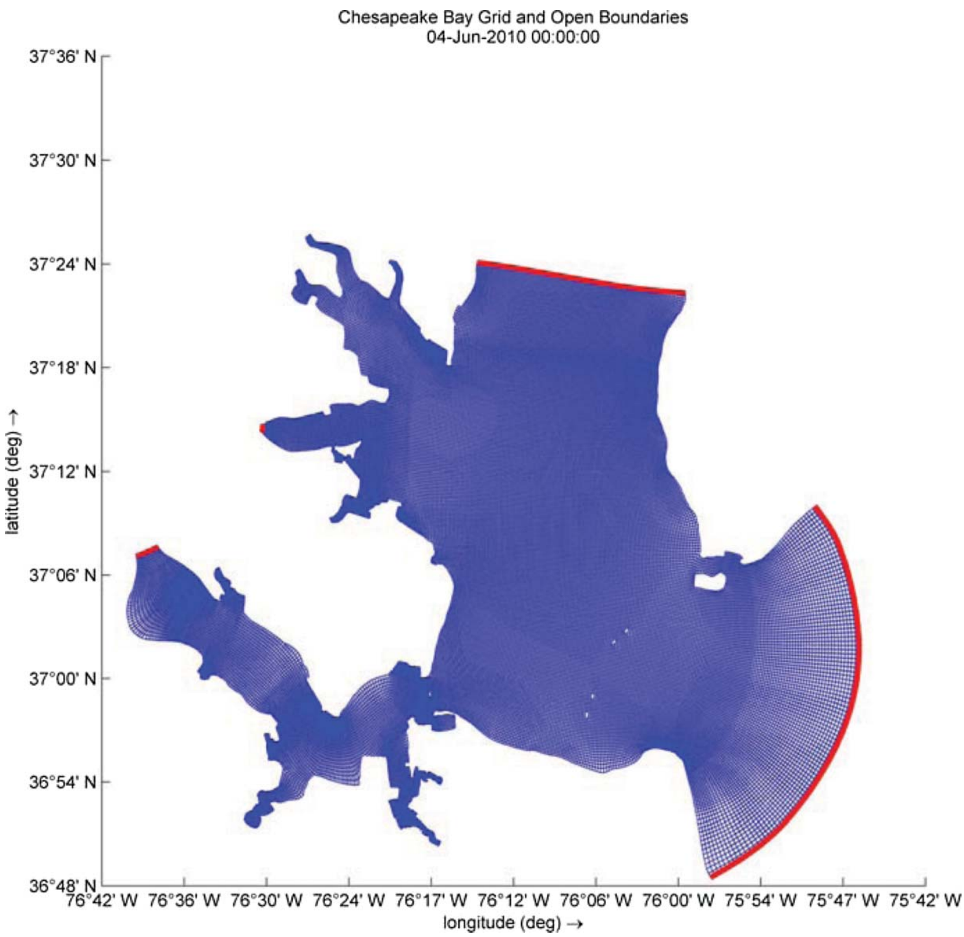

Figure 10. The Chesapeake Bay Delft3D domain. (Color figure available online.)

assimilation and post-processing. In addition to the standard water level and current forecasts, NCOM also generated three dimensional temperature and salinity fields at 3-hr intervals.

2.4. Delft3D

The Delft3D modeling system, developed by Delft Hydraulics (www.deltares.nl), is capable of simulating hydrodynamic processes due to wind, tides, and waves for coastal and estuarine areas. The model can be run in 2D or 3D configuration. A GUI-based preprocessing tool is used to generate curvilinear or rectangular grids in Cartesian coordinates and the post-processing tool allows production of graphics and plotting from the native binary model output format (Deltares 2011). Delft3D can be run on either a personal computer (PC) Windows or Linux platform; however, parallel processing capability is not currently implemented.

The system was configured with a curvilinear grid with approximately 500 cells in both x and y coordinates at 183 m spatial resolution (Figure 10) and 4 layers in the vertical direction distributed at the surface, 20%, 60%, and 100% of the total depth. Boundary conditions also came from the East Coast NCOM model. The 72-hour forecast Delft3D model simulation was performed on a single processor PC. The wall clock time for a single forecast run averaged approximately 5 hr. An example plot showing predicted water level for 0000 hr on June 14, 2010, is shown in Figure 11.

Table 1 summarizes configuration parameters for all of the models described herein. Spatial resolution, number of vertical layers, number of grid nodes, open boundary conditions (OBCs), surface forcing, and parallel operation are included.

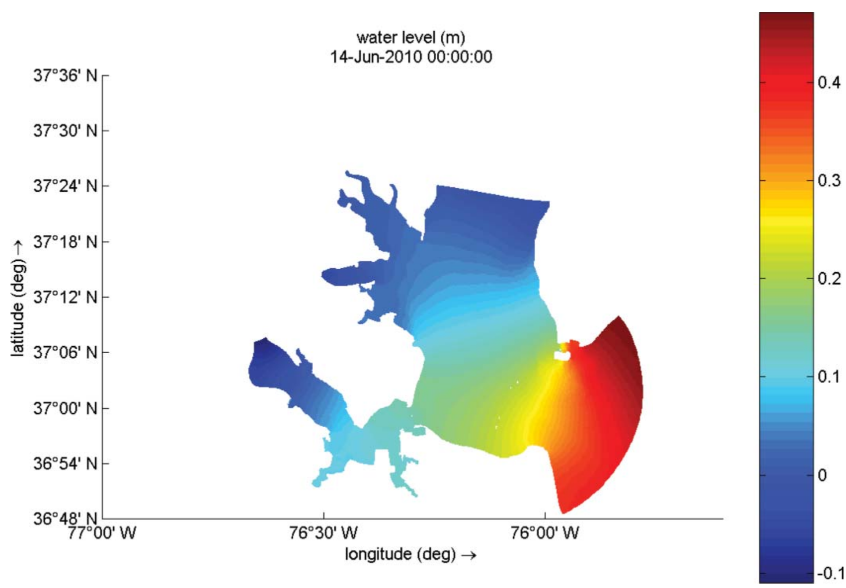

Figure 11. Example of Delft3D water level prediction. (Color figure available online.)

Table 1
Model configuration summary

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
Spatial resolution	15 m-2 km	150 m-12 km	500 m	183 m
Vertical layers	NA	41	29	4
No. of grid nodes	320 K unstructured	100 K unstructured	1million (1000 × 1000)	250 K (500 × 500)
OBC and surface forcing	N. Atlantic Tidal Database	EC-NCOM COAMPS	EC-NCOM COAMPS	EC-NCOM COAMPS
Parallel environment	Yes	Yes	Yes	No

3. Observational Field Data

3.1. Meteorological Conditions

Several severe storms passed the Chesapeake Bay region during the June 2010 exercise period, providing excellent opportunity for the model-data comparison. Figure 12 shows the wind speed, gusts and directions at the Chesapeake Bay Bridge Tunnel (CBBT) location during the exercise period. There are at least three occasions where wind speed exceeded 12 m/s and a total direction change (360 degrees) within just a few hour periods.

3.2. Water Level Data

For the water level analyses, validation data were obtained from NOAA/NOS water level gauge at CBBT (NOAA Station ID: CBBV2-8638863). The data at CBBT are recorded in

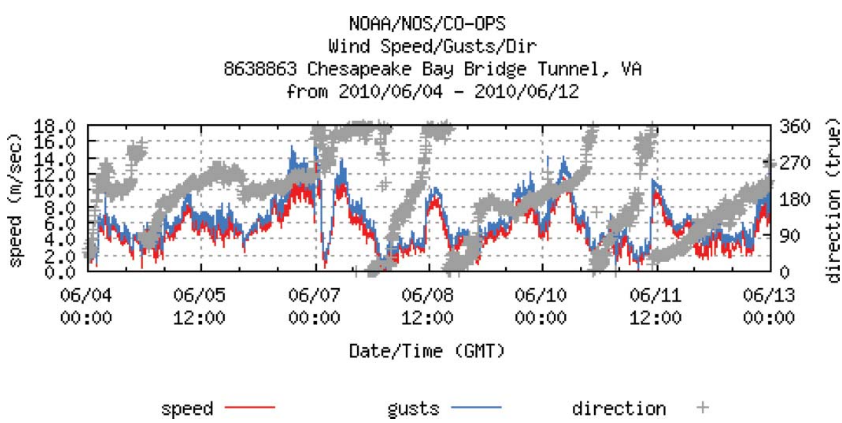

Figure 12. Wind speed, gusts and directions at CBBT location on June 4–12, 2010. (Color figure available online.)

6-min intervals. Data during the exercise period from the location were used for water level validation.

3.3. *Current ADP data*

Three downward-looking ADPs at locations in the bay were used to collect velocity information through the water column. Near real-time Acoustic Doppler Profiler (ADP) records collected by NOAA/NOS at Cape Henry (NOAA Station ID: CB0102), Thimble Shoal (NOAA Station ID: CB0301) and Naval Station (NOAA Station ID: CB0402) locations (Figure 13) were used to validate the model currents during the exercise period. The ADP bin size was 1 m and the sampling rate was 6 min. No detiding procedure has been applied. Since the ADP data used are near real-time, they have not been post processed through the standard NOAA Quality Assurance/Quality Control (QA/QC) procedure. Industry standard procedures were followed to identify, gap-fill, and interpolate missing records.

4. Validation Test Results

The data collected by NOAA/NOS during the exercise were used for model validation and comparison. Figure 13 shows the locations of water level gauge at CBBT and NOAA/NOS ADP current meters at Cape Henry, Thimble Shoal, and Naval Station.

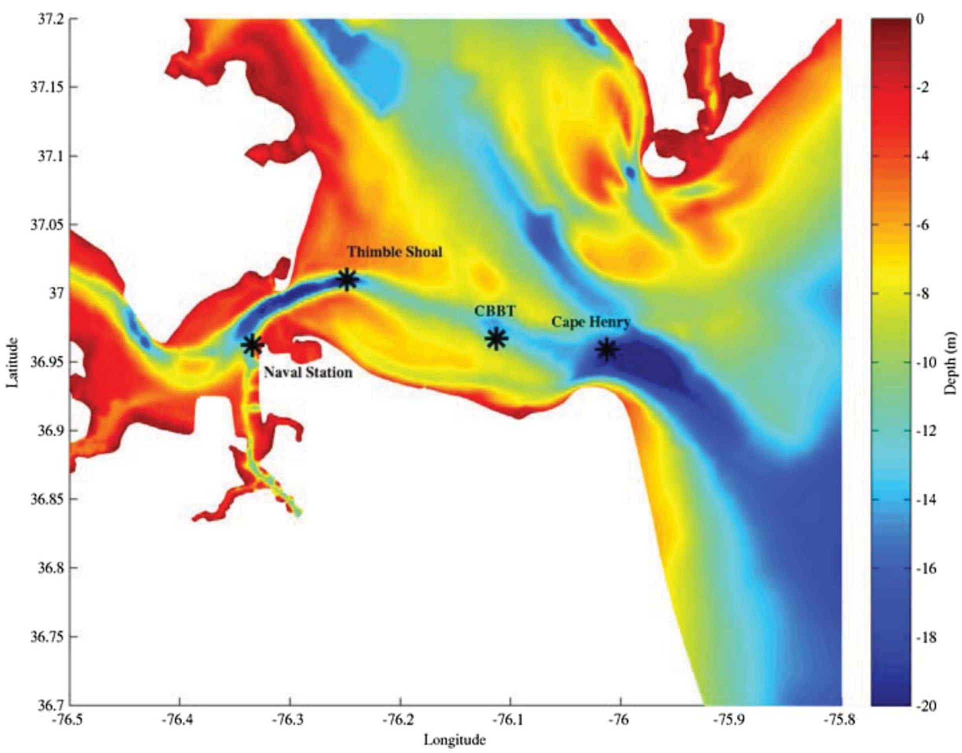

Figure 13. ADCIRC bathymetry with validation locations. (Color figure available online.)

4.1. Water Levels

For the water level validation, 6-min interval water level data collected at CBBT are used for the validation. The model-predicted water level fluctuations are referenced to the Mean Sea Level (MSL) while observational tidal gauges are generally referenced to the NOAA mean lower low water datum (MLLW). Adjustments were made to the model output to match the tidal vertical datum in order to make the statistical comparisons. The four modeled water level time series from ADCIRC2D, ADCIRC3D, NCOM and Delft3D results were de-trended and then plotted along with tidal gauge data from CBBT in Figure 14. All four models performed reasonably well for water level prediction. ADCIRC3D tends to overestimate the water levels because the daily open boundary condition provided by NCOM introduces a weak tidal signal to the domain in addition to the tidal constituents provided by the external dial database. Blain et al. (2012) investigates the sources of error in predicting water levels and reports that using the external tidal database only for tidal forcing leads to better predictions. Delft3D results showed a slight phase lag. NCOM shows a phase lead; ADCIRC has good phase characteristics. Table 2 shows the RMSE and correlation coefficient with respect to water level during June 6–14, 2010, for each of the models.

As shown in Table 2, all four models predict the water levels at the Chesapeake Bay Bridge Tunnel measurement station with a high correlation coefficient ($R > 0.77$). ADCIRC2D predictions for the water levels have the least error with the highest correlation

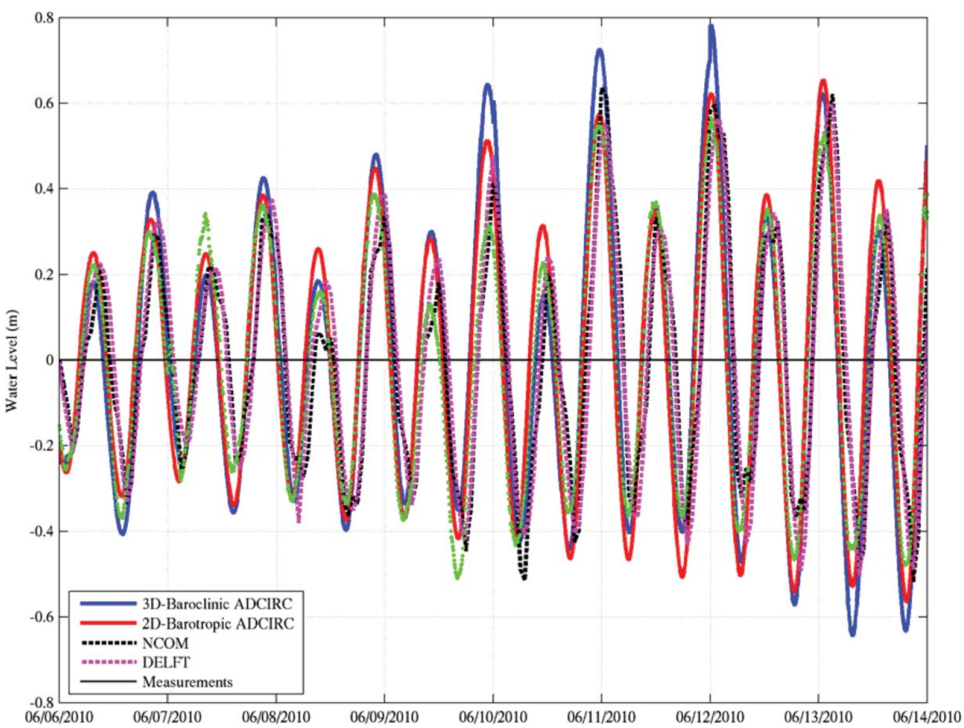

Figure 14. The water surface elevation measured by Chesapeake Bay Bridge Tunnel tide gauge vs. model results between June 6 and 14, 2010. (Color figure available online.)

Table 2
Summary of water level statistics

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
Correlation coefficient	0.903	0.865	0.796	0.773
Root Mean Square Error (m)	0.131	0.161	0.171	0.183

coefficient of 0.9. The ADCIRC3D follows with a correlation coefficient of 0.87. NCOM predicts the water levels with a correlation coefficient of almost 0.8 and Delft3D produces water level predictions with the least correlation. The performance of the models in predicting the water levels was also evaluated using the RMSE. Once again ADCIRC2D performs the best and results in the least error while Delft3D produces the largest error. ADCIRC2D has the highest resolution over the shallow coastal waters, which is expected to be an important reason for better model performance. ADCIRC has been used for numerous coastal surge and inundation studies and is used operationally during hurricane season. Because of that, the model has been developed towards getting more accurate water level results and the performance of ADCIRC for water level predictions may have been expected to be better than NCOM and DELFT3D. Although NCOM assimilates water level data, in this application NCOM water level predictions at this relatively shallow nearshore location are of poorer quality than those of ADCIRC.

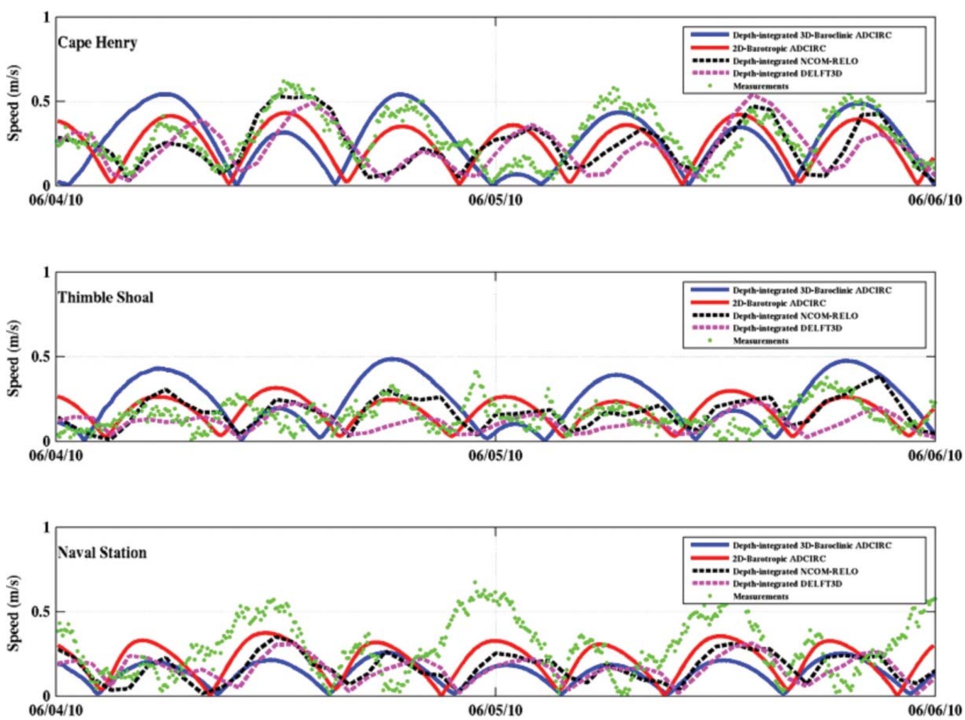

Figure 15. Depth-integrated currents measured at NOAA current meter stations; Cape Henry, Thimble Shoal, and Naval Station; compared with the model results from ADCIRC2D, ADCIRC3D, R-NCOM, and DELFT3D on June 4–6, 2010. (Color figure available online.)

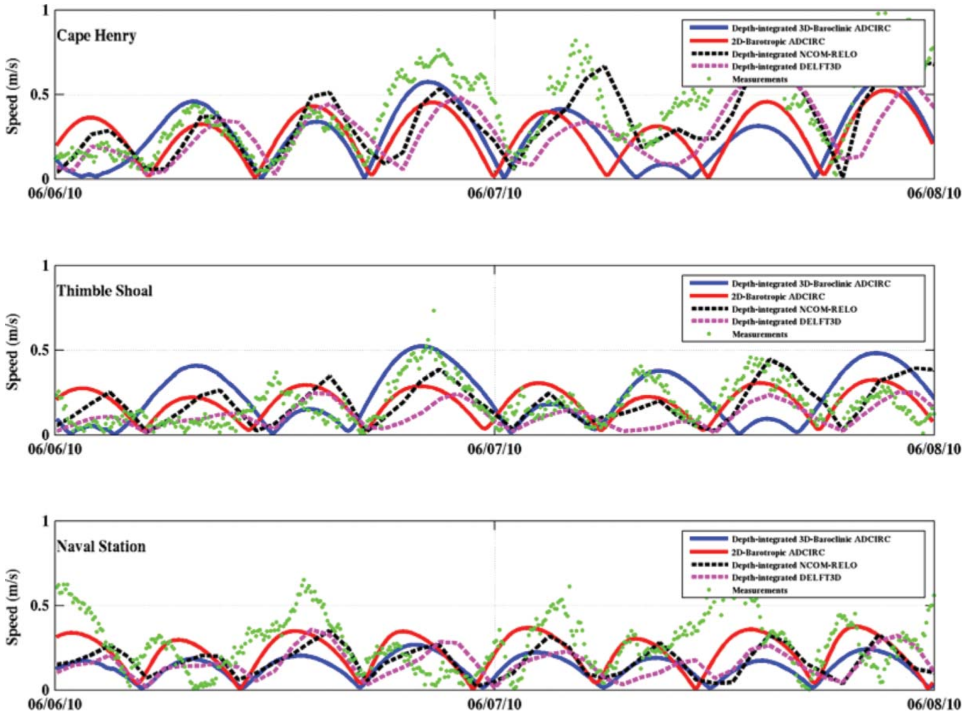

Figure 16. Depth-integrated currents measured at NOAA current meter stations; Cape Henry, Thimble Shoal, and Naval Station; compared with the model results from ADCIRC2D, ADCIRC3D, R-NCOM, and DELFT3D on June 6–8, 2010. (Color figure available online.)

4.2. Vertically-Integrated Currents

Near real-time NOAA/NOS ADP records at three locations have been used to validate the model currents during the exercise period. Figures 15–19 show the depth-integrated measured currents and the depth-integrated model predictions for successive two-day periods at Cape Henry, Thimble Shoal, and Naval Station. ADCIRC2D and ADCIRC3D directly output the depth-integrated currents. For NCOM and Delft3D, the depth-varying currents through the water column were averaged for comparison. The measured currents exhibit semi-diurnal variability with a mean magnitude hovering near 0.5 m/s; peak currents reach 1 m/s on only a couple of occasions near the end of the time period, June 10–14. It may be seen in the figures that all four models did fairly well in predicting the current magnitude. No single model is observed to stand out with its accuracy and performance according to these qualitative comparisons. In general, all four models seem to underestimate the currents.

Tables 3–5 and Figure 20 show the correlation coefficients of depth-integrated currents for all four models at the Cape Henry, Thimble Shoal, and Naval Station locations during June 4–10, 2010. The statistics were calculated for each 48-hr period as well as for the whole 6-day period. NCOM has the highest correlation coefficient (0.745) at Cape Henry while the other models perform similar. On the other hand, ADCIRC2D shows the highest correlation coefficients at Thimble Shoal and Naval Station. A higher correlation coefficient may be considered to indicate less phase error.

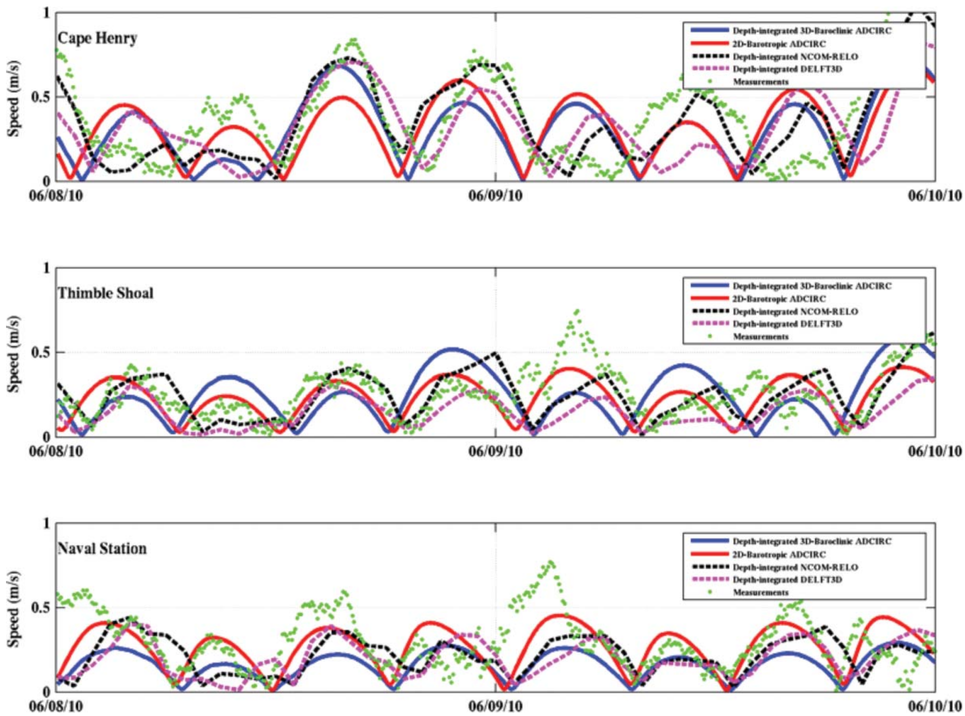

Figure 17. Depth-integrated currents measured at NOAA current meter stations; Cape Henry, Thimble Shoal, and Naval Station; compared with the model results from ADCIRC2D, ADCIRC3D, R-NCOM, and DELFT3D on June 8–10, 2010. (Color figure available online.)

Tables 6–8 and Figure 21 show the root-mean-square errors (RMSE) of depth-integrated currents for all four models at the three stations. Overall, NCOM has the smallest error over the 6-day period at Cape Henry, and ADCIRC2D has the smallest error over the 6-day period at Thimble Shoal and at Naval Station.

NCOM is the only model in this study with data assimilation that is used to improve model performance. As a result, NCOM produces the best predictions at Cape Henry, which is the deepest station closer to the Chesapeake Bay mouth. ADCIRC performs better at shallower stations probably because of the higher grid resolution at shallower locations. ADCIRC2D predicts depth averaged currents more accurately than ADCIRC3D. The winds used in ADCIRC3D are a major source of error for current predictions while the

Table 3
Correlation coefficients at Cape Henry for depth-integrated currents

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4–6/6	0.513	0.381	0.485	0.220
6/6–6/8	0.494	0.545	0.706	0.539
6/8–6/10	0.375	0.469	0.824	0.466
6/4–6/10	0.439	0.455	0.745	0.463

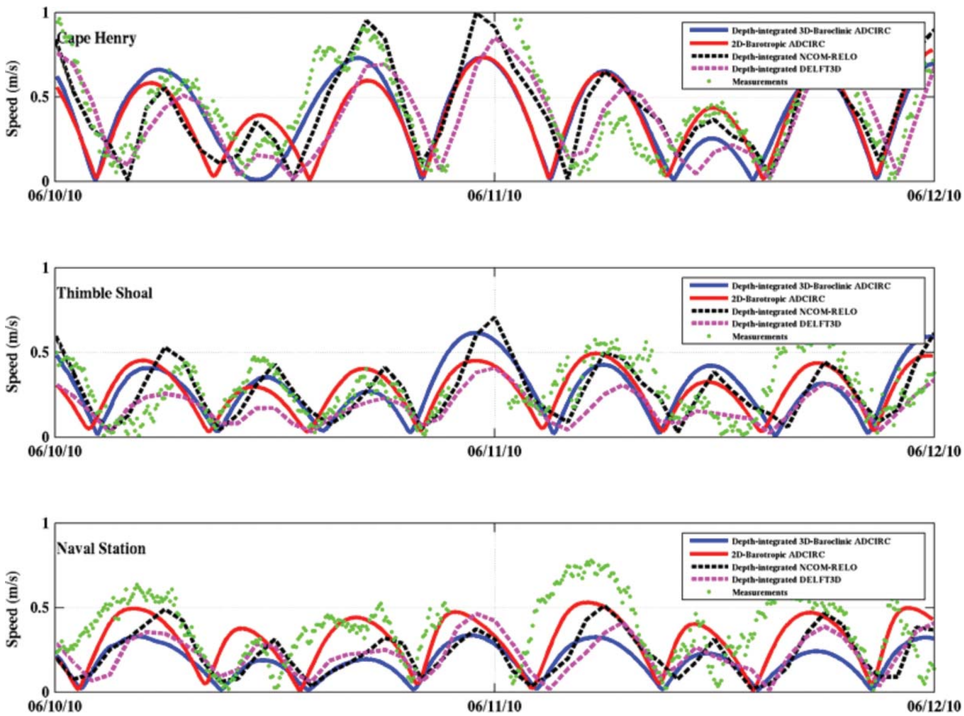

Figure 18. Depth-integrated currents measured at NOAA current meter stations; Cape Henry, Thimble Shoal, and Naval Station; compared with the model results from ADCIRC2D, ADCIRC3D, R-NCOM, and DELFT3D on June 10–12, 2010. (Color figure available online.)

Table 4
Correlation coefficient at Thimble Shoal for depth-integrated currents

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4–6/6	0.168	0.237	0.024	−0.370
6/6–6/8	0.390	0.429	0.328	0.182
6/8–6/10	0.597	0.223	0.555	0.590
6/4–6/10	0.491	0.299	0.442	0.343

Table 5
Correlation coefficient at Naval Station for depth-integrated currents

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4–6/6	0.365	−0.270	0.184	−0.024
6/6–6/8	0.271	0.021	0.005	0.073
6/8–6/10	0.419	0.084	0.067	0.056
6/4–6/10	0.344	0.027	0.083	0.039

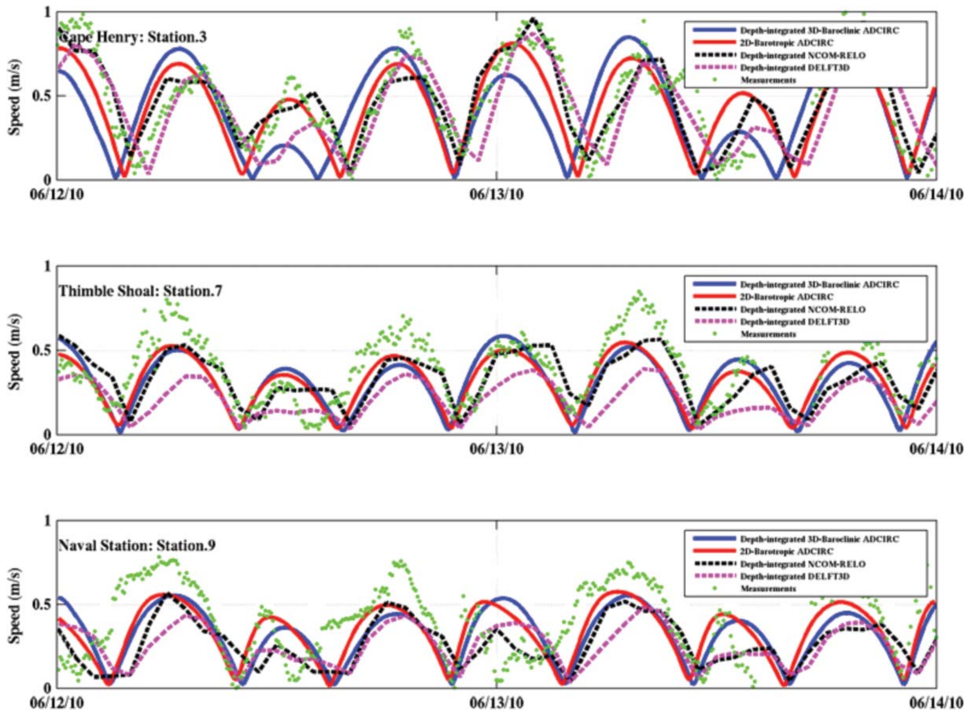

Figure 19. Depth-integrated currents measured at NOAA current meter stations; Cape Henry, Thimble Shoal, and Naval Station; compared with the model results from ADCIRC2D, ADCIRC3D, R-NCOM, and DELFT3D on June 12–14, 2010. (Color figure available online.)

Table 6
RMSE at Cape Henry for depth-integrated currents

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4–6/6	0.145	0.171	0.157	0.189
6/6–6/8	0.264	0.256	0.194	0.254
6/8–6/10	0.285	0.280	0.170	0.277
6/4–6/10	0.239	0.241	0.174	0.243

Table 7
RMSE at Thimble Shoal for depth-integrated currents

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4–6/6	0.108	0.151	0.123	0.129
6/6–6/8	0.117	0.141	0.136	0.141
6/8–6/10	0.123	0.183	0.139	0.165
6/4–6/10	0.116	0.159	0.133	0.146

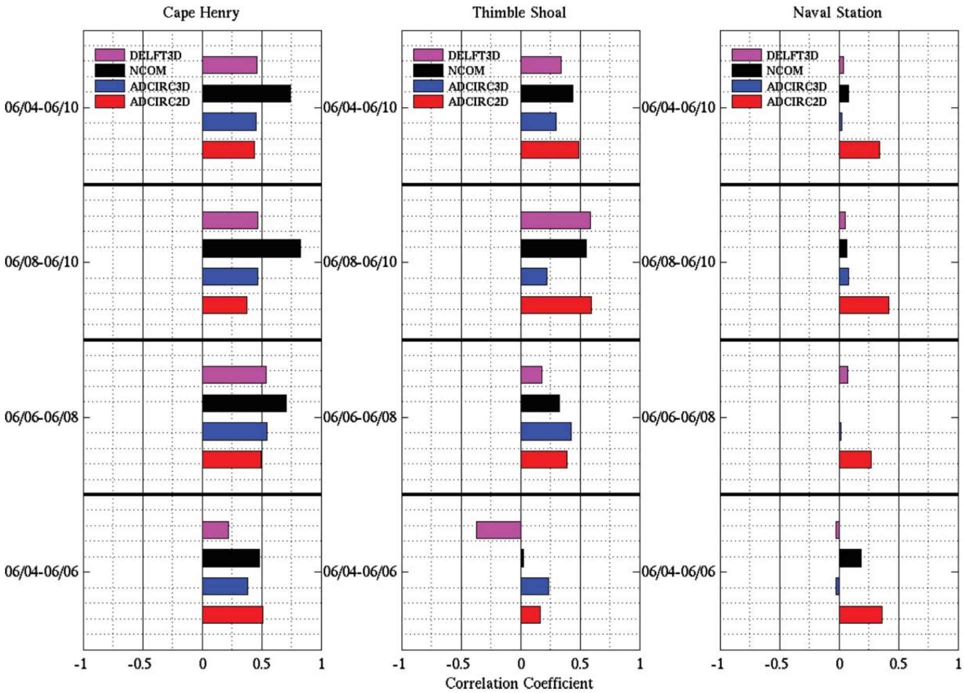

Figure 20. The correlation coefficients of numerical models for depth-integrated currents predictions between June 4 and 10, 2010, at Cape Henry, Thimble Shoal, and Naval Station locations. (Color figure available online.)

initialization of the ADCIRC3D by NCOM predictions may also decrease accuracy (Blain et al. 2012).

4.3. Vertical Variation of Currents

The horizontal currents over the water column of all three 3-dimensional models are compared with the NOAA ADP instruments at Cape Henry, Thimble Shoal, and Naval Station. Figures 22–26 show the currents at different times during the exercise. NCOM produces output at 7 (at Cape Henry and Naval Station) or 8 (at Thimble Shoal) vertical levels at the measurement locations. Delft3D has 4 vertical levels while ADCIRC3D has 41 levels at all three NOAA/NOS instrument locations.

Table 8
RMSE at Naval Station for Depth-Integrated Currents

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
6/4–6/6	0.177	0.215	0.213	0.227
6/6–6/8	0.174	0.201	0.211	0.211
6/8–6/10	0.152	0.194	0.197	0.206
6/4–6/10	0.168	0.203	0.207	0.215

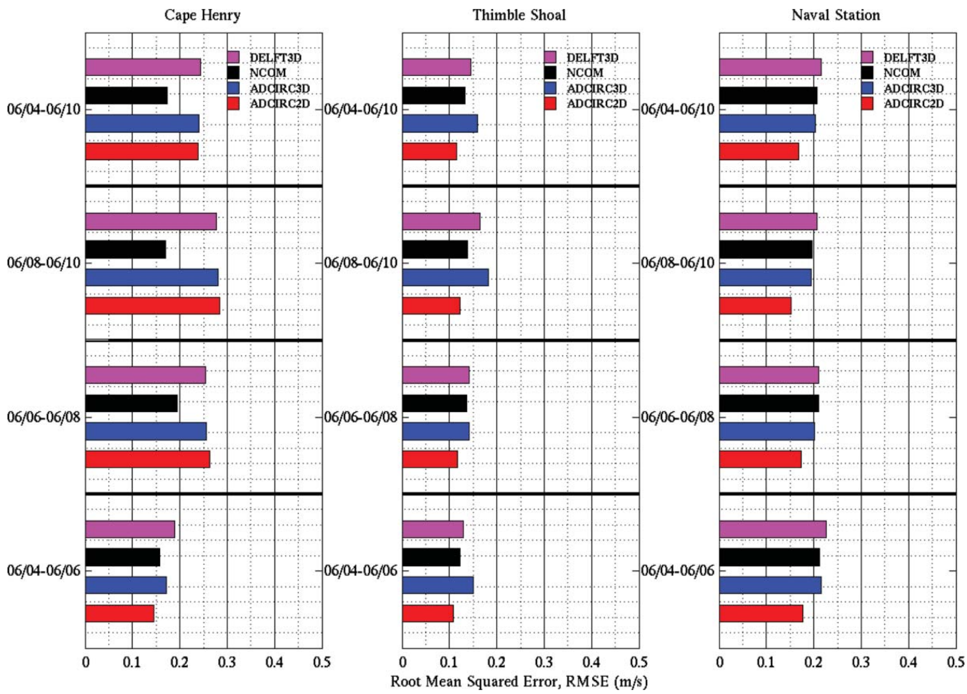

Figure 21. The Root Mean Squared Error (RMSE) of numerical models for depth-integrated currents predictions between June 4 and 10, 2010, at Cape Henry, Thimble Shoal, and Naval Station locations. (Color figure available online.)

As ADCIRC3D, NCOM, and Delft3D have different vertical resolutions over the water column and use different bathymetry databases, correlation coefficients and RMSE are computed only at common depths where all three models and ADP data have current velocities. The model results cannot be compared to the measurements at the surface since the ADP is downward looking and there is a 1.4 m blanking distance. The bottom level is also not used since the depths within Delft3D are deeper than both the observations and the other models at Thimble Shoal. As a result, the model-data comparisons are done at the 20% and 60% depth levels of Delft3D. The NCOM and ADCIRC3D results have been interpolated to make the comparisons at the same depths.

Tables 9–11 show the correlation coefficients of model results compared to the ADP measurements at the three locations during June 4–10, 2010. The statistics were calculated

Table 9

Correlation Coefficient of current Profiles at Cape Henry at 0.2D and 0.6D depth

	ADCIRC3D		NCOM		Delft3D	
Depth Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4–6/6	−0.223	0.640	0.499	0.514	0.187	−0.235
6/6–6/8	0.118	0.773	0.059	0.414	−0.126	0.148
6/8–6/10	0.621	0.408	0.601	0.694	0.373	0.164

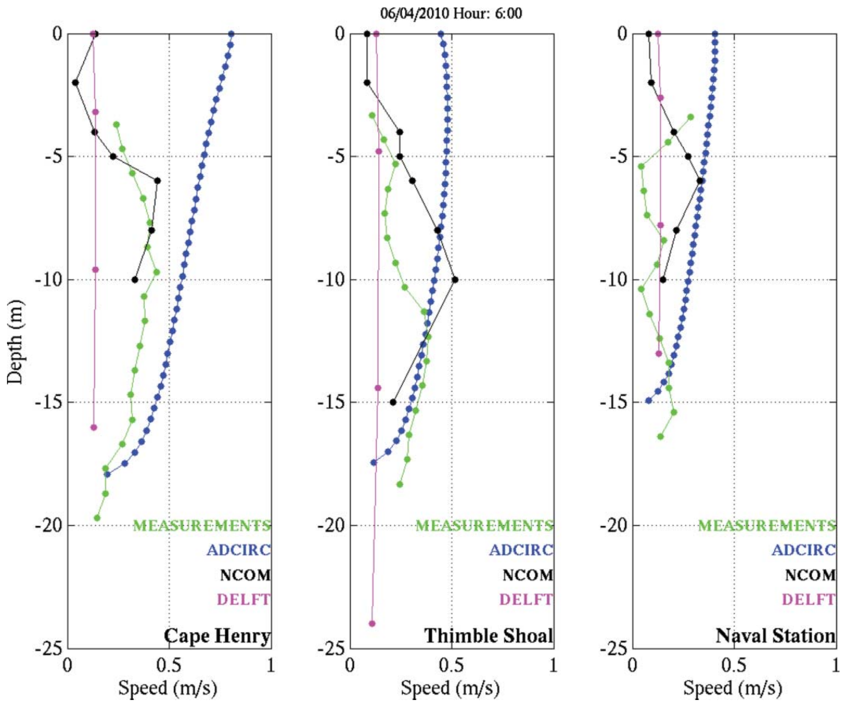

Figure 22. The depth-varying current measurements and model results at Cape Henry, Thimble Shoal and Naval Station NOAA/NOS instrument locations at 0600 hr on June 4, 2010. (Color figure available online.)

Table 10
Correlation Coefficient of current Profiles at Thimble Shoal at 0.2D and 0.6D depth

	ADCIRC3D		NCOM		Delft3D	
Depth Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4–6/6	−0.173	0.160	−0.125	0.356	−0.289	−0.131
6/6–6/8	0.245	0.262	0.148	0.542	0.100	−0.052
6/8–6/10	0.292	−0.009	0.130	0.099	0.279	−0.186

Table 11
Correlation Coefficient of current Profiles at Naval Station at 0.2D and 0.6D depth

	ADCIRC3D		NCOM		Delft3D	
Depth Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4–6/6	−0.037	0.073	−0.173	0.137	−0.016	−0.177
6/6–6/8	−0.111	−0.075	0.088	−0.113	0.165	0.038
6/8–6/10	0.238	0.169	−0.138	−0.188	0.017	0.145

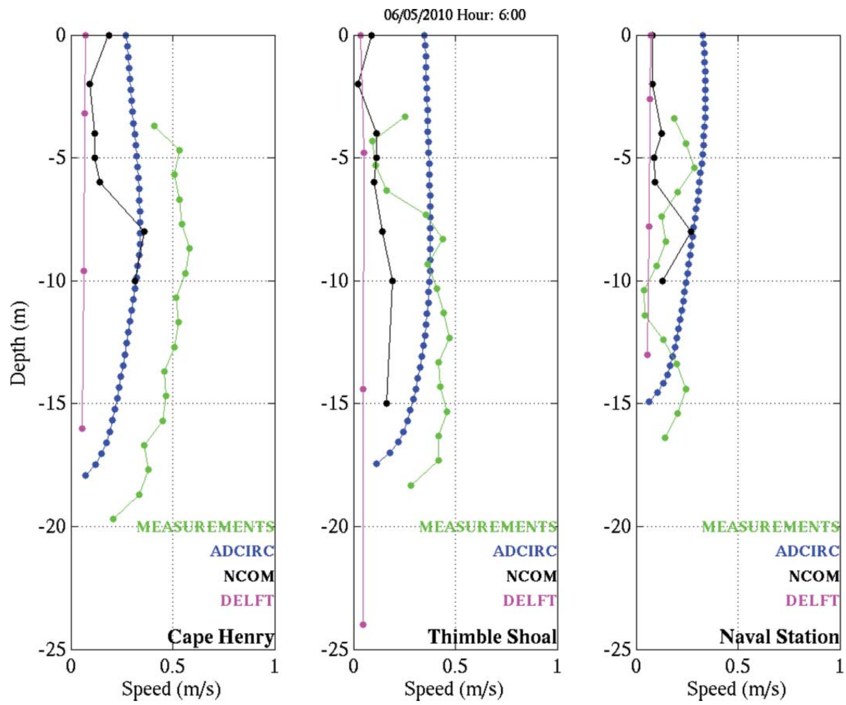

Figure 23. The depth-varying current measurements and model results at Cape Henry, Thimble Shoal and Naval Station NOAA/NOS instrument locations at 0600 hr on June 5, 2010. (Color figure available online.)

at the 20% and 60% Delft3D depth levels, denoted 0.2D and 0.6D, respectively, using hourly measurements and hourly model results. The results show that each model has the highest correlation coefficient at least once at one of the stations during the three 48-hr periods considered. ADCIRC3D and NCOM perform better than Delft3D at Cape Henry and Thimble Shoal. In fact, Delft3D has the highest correlation only once and at the Naval Station. The correlation coefficients are higher at Cape Henry indicating that the model phase is in better agreement with the measurements at that location. Neither ADCIRC3D nor NCOM is consistently better than the other at Cape Henry. ADCIRC3D predictions are better correlated with the measurements at 0.2D level at Thimble Shoal while NCOM has the highest correlation at all times at the 0.6D level at the same location. It may be seen that as we move further upstream in the bay, the phase errors of all 3 models increase. This may be attributed to the increased nonlinearities at those shallower locations in which proper physics are not incorporated in the models.

The RMSEs were calculated at 0.2D and 0.6D depth levels using hourly measurements and hourly model data and are presented in Tables 12–14. NCOM current predictions have the least error at 0.2D vertical level at Cape Henry while ADCIRC3D has the least error at 0.6D for the first 2-day periods. Delft3D generally has the largest error in predicting currents. At Thimble Shoal, NCOM results have the least error at 0.6D while ADCIRC3D and Delft3D produce current predictions closer to the measurements at 0.2D. Finally, at Naval Station ADCIRC3D results show the least error at 0.2D and NCOM results have the smallest error at 0.6D while Delft3D produces the highest error at both depths. Overall, all

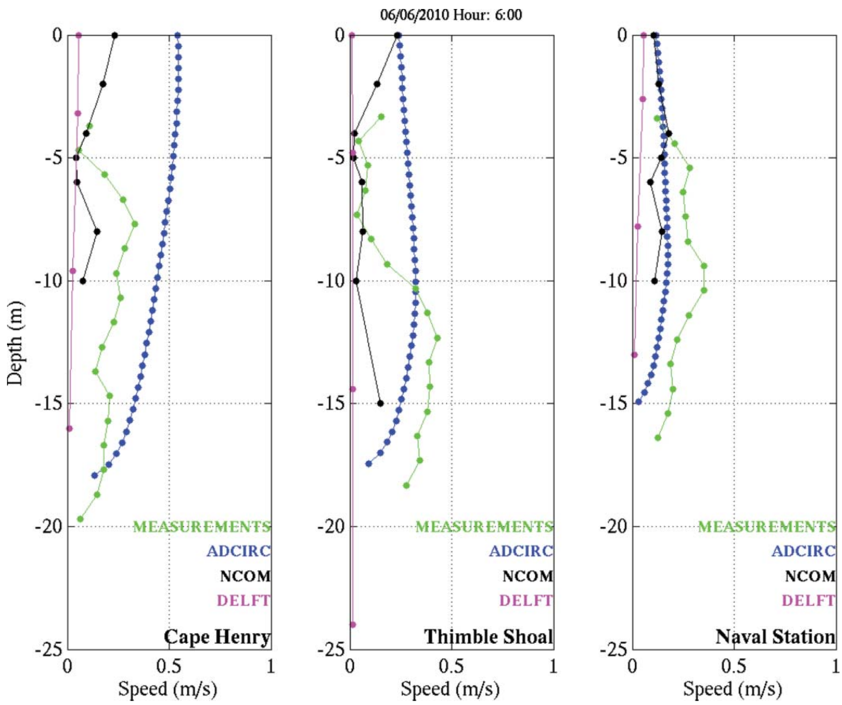

Figure 24. The depth-varying current measurements and model results at Cape Henry, Thimble Shoal, and Naval Station NOAA/NOS instrument locations at 0600 hr on June 6, 2010. (Color figure available online.)

Table 12
Root-mean-square error of current Profiles at Cape Henry at 0.2D and 0.6D depth

	ADCIRC 3D		NCOM		Delft3D	
Depth Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4–6/6	0.271	0.149	0.187	0.154	0.236	0.250
6/6–6/8	0.331	0.226	0.316	0.287	0.348	0.342
6/8–6/10	0.253	0.254	0.237	0.195	0.286	0.299

Table 13
Root-mean-square error of current Profiles at Thimble Shoal at 0.2D and 0.6D depth

	ADCIRC3D		NCOM		Delft3D	
Depth Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4–6/6	0.196	0.250	0.142	0.164	0.140	0.201
6/6–6/8	0.167	0.239	0.170	0.182	0.155	0.227
6/8–6/10	0.192	0.308	0.199	0.233	0.216	0.260

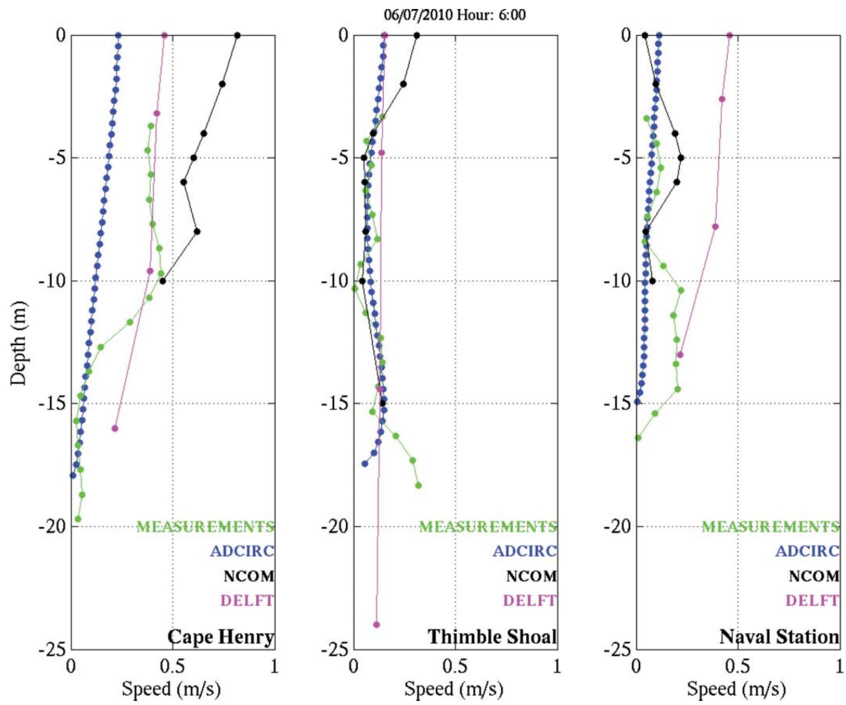

Figure 25. The depth-varying current measurements and model results at Cape Henry, Thimble Shoal and Naval Station NOAA/NOS instrument locations at 0600 hr on June 7, 2010. (Color figure available online.)

three models produce similar error in predicting the currents, but ADCIRC3D and NCOM produce more vertical variability and hence a more realistic current structure over the water column. Delft3D has only 4 vertical levels, and this may be one of the limiting factors leading to less accurate predictions.

5. System Requirements and Operational Related Issues

5.1. Hardware Requirements

ADCIRC2D: The system was designed to be independent of the hardware platform. The Chesapeake Bay System was run on the NRL Linux cluster as well as on the NAVO DSRC

Table 14
Root-mean-square error of current Profiles at Naval Station at 0.2D and 0.6D depth

	ADCIRC3D		NCOM		Delft3D	
Depth Date	0.2D	0.6D	0.2D	0.6D	0.2D	0.6D
6/4–6/6	0.149	0.202	0.188	0.181	0.221	0.219
6/6–6/8	0.134	0.221	0.144	0.198	0.246	0.238
6/8–6/10	0.186	0.208	0.223	0.220	0.289	0.241

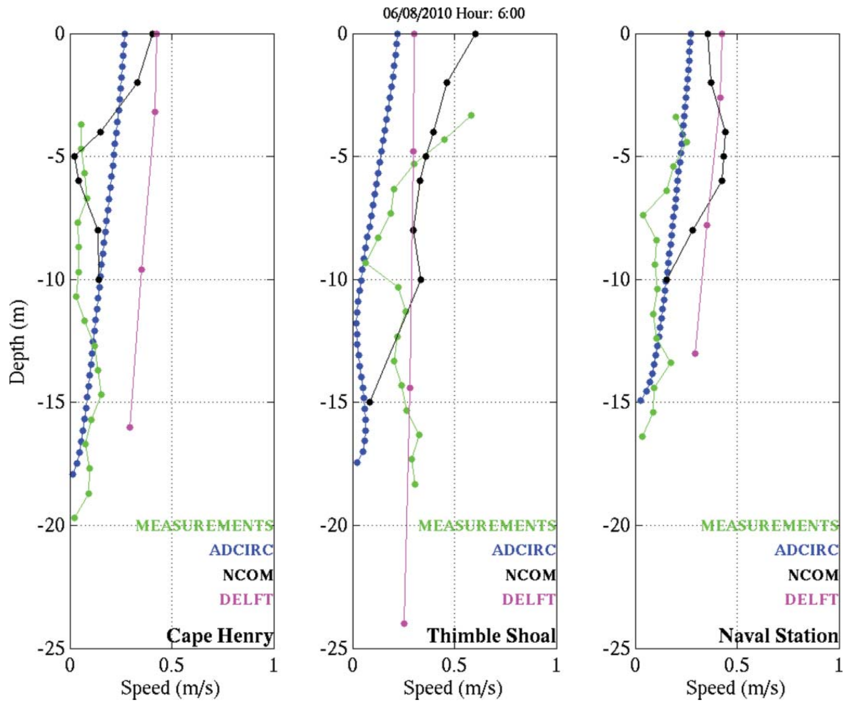

Figure 26. The depth-varying current measurements and model results at Cape Henry, Thimble Shoal and Naval Station NOAA/NOS instrument locations at 0600 hr on June 8, 2010. (Color figure available online.)

IBM-P6 platform. Both systems were running in real-time during the exercise period. The Linux version used 64 processors and took about 1-hr wall clock time to run 72-hr forecasts. The DSRC version required approximately the same time with the same configuration.

ADCIRC3D: This system was also designed to be independent of the hardware platform. In order to wait for the completion of NCOM output for the initial and boundary conditions, ADCIRC3D was run in delayed mode on the NRL SGE platform during the exercise period. Each 72-hr simulation with 64 CPUs took 4 hrs of wall clock time. Similar computation time could be expected for the DSRC platform since the SGE and the DSRC IBM-P6 are comparable with regard to processor speed.

NCOM: During the exercise, NCOM used the most computational resources: 5 hrs of wall clock time using 128 CPUs and produced raw output file sizes of 22GB/day. This is likely due to: (1) a large geographic domain containing more than one million grid points, (2) relative high spatial resolution at 500 m and small time step during integration, (3) large numbers of vertical layers, and 4) the NCODA data assimilation procedure added an additional hour of CPU time.

DELFT3D: The model was configured to run on a single CPU PC, with a configuration consisting of 250,000 cells with 4 vertical layers. A 72-hr run took 4–5 hrs of wall clock time, and the output files required about 2GB of disk space.

In additional to the computational requirements, one other factor to be considered for operational daily forecasts is the size of the model output. For example, a typical NCOM output in compressed format takes more than 22GB of disk space. Archiving and purging

Table 15
Summary of model computation resource requirements

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
72-hr run on Davinci	1 hour wall clock on 64 CPUs	NA	5 hour wall clock on 128 CPUs	NA
72-hr run On NRL Linux cluster	1 hour wall clock on 64 CPUs	4 hour wall clock on 64 CPUs	NA	NA
72-hr run on PC	NA	NA	NA	5 hour single processor CPU
Output file size	1GB	5GB	22GB	2GB
CPU in second /cell/day run	0.3	3.0	1.5	0.05
Ratio	6	60	30	1

procedures need to be carefully evaluated to prevent disk storage issues. This is especially true for local workstations with limited storage capacity.

The computational resources required to run a typical 72-hr forecast for the Chesapeake Bay region for each of the four models based on the present configuration are summarized in Table 15. Using Delft3D as a benchmark, the ratio of CPU per cell per day for each model was estimated at the end of Table 15.

5.2. *Personnel Requirements*

Personnel resource requirements for running a new geographic region on a regular basis are evaluated based on three categories: (1) initial training, (2) set-up and configuration of a new area, and (3) daily monitoring and maintenance. Some of those requirements for each modeling system are summarized in Table 16.

Initial Training: All systems have fairly user-friendly software installation scripts and documentation (user's guide and software manual). Two-day training/tutorial sessions should cover all the necessary steps in setting up new geographic domain, using mesh generation tools, modifying run scripts, and operational and maintenance issues.

Setting up a new domain: Both NCOM and Delft3D have a relative straightforward procedure in setting up a new domain since rectangular grid can be generated automatically once the user specifies the latitude and longitude of the four corners of the model domain. On the other hand, due to the nature of the triangular unstructured mesh system used by ADCIRC, mesh generation cannot be fully automated at present. One of the concerns regarding the finite element based coastal forecasting system is the time and effort required to setup a new geographic region and generate a mesh. The MeshGUI software was developed to create mesh, and a step-by-step user guide describing how to generate the mesh from scratch was compiled to assist the end users (Blain et al. 2008). Using the NRL in-house developed mesh generation GUI tools, users are able to generate a new domain mesh file for ADCIRC within an hour.

Table 16
Model resource requirements

	ADCIRC2D	ADCIRC3D	NCOM	Delft3D
Mesh/grid generation	1 hour with MeshGUI	1 hour with MeshGUI	2–3 hours	Pre-processing grid GUI
System config./testing	1 week	1 week	1 week	1 week
Operational	Automatic	Automatic	Automatic	Perl based
Runs	Shell scripting	Shell scripting	Shell scripting	Scripting
Initial training	1 personnel for 2 days	1 personnel for 2 days	2-3 personnel for 2 days	1 personnel for 2 days

Daily monitoring and maintenance: All four systems employ scripts for automated daily operation once the system is configured. Daily forecasts are fully automated requiring no special maintenance. Minimal monitoring is needed to restart the system in case of interruption due to (1) missing or delayed input fields, (2) hardware failure, and (3) insufficient local storage space.

6. Summary and Conclusions

Three coastal models—one community code-ADCIRC2D/3D, one proprietary model-NCOM, and one commercial software-Delft3D—have been configured, tested, and validated for the lower Chesapeake Bay region during a Navy exercise in June 2010. Water level predictions are compared with a NOAA/NOS water level gauge at the Chesapeake Bay Bridge Tunnel location while the current predictions are validated with ADP measurement records at Cape Henry, Thimble Shoal, and Naval Station. Standard statistical metrics such as correlation coefficient and RMSE are computed. Both vertically integrated currents and currents at various vertical water depths are compared.

The validation results and statistics for surface elevation and vertically integrated currents show ADCIRC2D and NCOM yield better statistics, in terms of correlation and RMSE, than the other two models. For the horizontal currents in the vertical direction, the ADCIRC3D and NCOM showed better agreement with the NOAA ADP measurements.

All three models, ADCIRC3D, NCOM, and Delft3D, produced currents that were not well correlated with the meteorological observations. This raises the possibility that the meteorological model forcing was in some way suboptimal. A closer look at the COAMPS, particularly the spatial and temporal resolutions, indicated the 27 km resolution at 3-hr interval is not adequate to resolve the fast passing weather system during the exercise period. An improved method of assimilating real-time meteorological station data should be investigated to improve the meteorological forcing input. Blain et al. (2012) showed that surface wind forcing may be a significant source of error for forecasts in coastal waters and enhancing the spatial and temporal resolution of wind predictions will improve ocean model's predictability of coastal currents.

Large errors in current magnitude were found at several levels over the water column from the model-data comparisons. The reasons for those discrepancies and low correlation coefficient values are likely due to (1) water depth mismatches among models and measurement location, (2) inadequate spatial and temporal resolutions for COAMPS wind forcing, or (3) insufficient number of vertical layers for Delft3D. The winds are one of the dominant mechanisms for the currents and model predictions may be improved especially if atmospheric forcing is provided at a higher spatial and temporal resolution since several strong wind events occurred over the Chesapeake Bay area during the validation period.

The resource requirements for each modeling system have also been evaluated. This includes benchmark tests on grid generation, model setup and configuration, as well as hardware and operational requirements. ADCIRC2D and NCOM are configured to run automatically in real-time at the Navy DoD Supercomputing Resources Center (DSRC). ADCIRC3D can be configured to run automatically. Delft3D currently runs on a single processor PC or Linux platform and it cannot be configured to run at the DSRC until the parallel version has been implemented.

In summary, water levels and currents predicted by ADCIRC and NCOM models showed better agreement than that of Delft3D when compared with the Chesapeake Bay

field data during the Navy exercise. The present four vertical layer configuration in Delft3D is not adequate to resolve the dynamics in the water column, and the bathymetry data used in the morphological grid should be verified with NAVO DBDB2 bathymetry database or field survey data. All models would benefit from higher spatial and temporal resolution meteorological forcing.

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